GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. G-41-606 (R5437-6A0) GTRC/~~GIT~~ DATE 12/10/85

Project Director: Dr. Joseph Ford School/~~Lab~~ Physics

Sponsor: Department of Energy
Oak Ridge Operations, TN

Type Agreement: Mod. A007 to Contract DE-AS05-81ER40003

Award Period: From 12/1/85 To ~~11/30/86~~ 2-28-87 (Performance) 11/30/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$ 80,000	$ 80,000
Funded:	$ 80,000	$ 80,000

Cost Sharing Amount: $ None Cost Sharing No: N/A

Title: Dissipative Effects in the Beam-Beam Interaction of Intersecting Storage Rings

ADMINISTRATIVE DATA

OCA Contact Brian J. Lindberg X4820

1) Sponsor Technical Contact:
Dr. Richard Sah
U. S. Department of Energy
Division of High Energy Physics
Mail Stop ER-224,GTN
Washington, DC 20545
(301) 353-2821

2) Sponsor Admin/Contractual Matters:
Ms. Marlena Cansler
Procurement and Contracts Div.
DOE, Oak Ridge Operations
P. O. Box E
Oak Ridge, Tennessee 37830
(615) 576-7599

Defense Priority Rating: N/A Military Security Classification: N/A
(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached Gov't Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT, if acquired by us and listed in Appendix "A"

COMMENTS:

Modification No. A007 adds $80,000 as follow-on to G-41-638. New Project Number is required because of separate financial reporting requirements.

Total contract value (including previous project numbers) now: $406,000

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FORM OCA 65:285

GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 5-22-87

Project No. G-41-606

School/~~Lab~~ Physics

Includes Subproject No.(s) N/A

Project Director(s) J. Ford — GTRC / ~~GIT~~

Sponsor Department of Energy

Title Dissipative Effects in the Beam-Beam Interaction of Intersecting Storage Rings

Effective Completion Date: 2/28/87 (Performance) 2/28/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [X] Closing Documents
- [X] Final Report of Inventions - Questionnaire sent to P.I.
- [X] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. G-41-638

Continued by Project No.

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Other Duane H.
Angela DuBose
Russ Embry

FORM OCA 69.285

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U.S. DEPARTMENT OF ENERGY

NOTICE OF ENERGY RD&D PROJECT

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FORM APPROVED
OMB NO. 38 R-0190

escriptive title of work Dissipative Effects in the Beam-Beam Interaction of Intersecting Storage Rings

erforming organization control number G-41-606

Vork status ☐ New ☐ Continuing ☐ Terminated

3. Contract or grant number DE-AS05-81ER40003, A007

Contractor's principal investigator/project manager and address where work is performed

A. Name (Last, First, MI) FORD, Joseph B. Phone: FTS- (404) 894-5255

C. Research organization School of Physics, Georgia Institute of Technology
business address: Street 210 North Avenue Com.-
City Atlanta, Georgia 30332 State Zip

A. Name of performing organization Georgia Institute of Technology (Organization) School of Physics (Department)

B. Mailing address (If different from 4C)

C. Circle only one code for TYPE OF ORGANIZATION PERFORMING R&D (See instructions):
CU FF IN NP ST TA US XX EG

D. Location where the work is being performed

E. Country sponsoring research

Supporting organization

A. Program division or office (Full name) Division of High Energy Physics

B. Technical monitor (Last, First, MI) Blumberg, Roy (Dr.) C. Phone: FTS- (301) 353-2821

D. Address (If different from DOE Hqs.)
Com.-

E. Administrative monitor (Last, First, MI) Carringer, Joyce, DOE Oak Ridge (615) 576-7564

Project schedule

A. Start date 1 December 1986 (Month) (Year) B. Expected completion date 30 November 1987 (Month) (Year)

Funding in thousands of dollars (Funds represent budget obligations for operating and capital equipment)

	Funding organization(s)	Current FY	Next FY
A.	DOE	$ 80,000	$ 87,300
B.			
C.			

D. For DOE projects, enter budgeting and reporting classification code

E. Interagency agreement (Specify funding agency)

F. Agency in-house effort (Check if applicable) ☐

G. EPA "pass-thru" funding (Check if applicable) ☐

Note: Funding Section utilization is optional on Federal Financial Assistance Programs: grants, direct payments, cooperative agreements, loan guarantees, and other related programs.

. Descriptive summary of work (Limit to 200 words. Include objective, approach, results to date and their significance, and expected product. Quantify where possible). This proposal seeks continuing support for an ongoing resarch investigation of long-term stability in intersecting, counter-rotating beams of protons and antiprotons confined within high-energy storage rings. Although the dissipative effect of synchrotron radiation in these hadron colliders is anticipated to be a relevant feature affecting beam lifetime, very little is known regarding stability in such many-dimensional, weakly dissipative systems. The work proposed here will analyze the affect of weak dissipation on dynamical instabilities induced by the interaction of synchro-betatron resonances. The object of the research is to obtain conditions for global beam stability over long-time scales as a function of various machine parameters.

G-41-606

3c..

GEORGIA TECH RESEARCH CORPORATION

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0420

Telex: 542507 GTRCOCAATL
Fax: (404) 894-3120

Phone: (404) 894- 4817

Refer to: JG/02.141.002.87.002

July 29, 1986

Office of Energy Research
Division of High Energy Physics, ER-224
U.S. Department of Energy, GTN
Washington, D.C. 20545

Attention: Dr. Roy Blumberg

Subject: Contract DE-AS05-81ER40003

Dear Sir:

Georgia Tech Research Corporation is pleased to submit the enclosed proposal for "Dissipative Effects in the Beam-Beam Interaction of Intersecting Storage Rings". This proposal was prepared by Dr. Joseph Ford. Regents Professor of Physics, Georgia Institute of Technology. This proposal is for continuation of the research currently being performed under the subject contract.

A progress report for the work authorized under modification A007 is included along with a description of the proposed research for the year beginning 1 December 1986. Georgia Tech Research Corporation requests that any award resulting from this proposal be a modification to the existing contract.

We appreciate the opportunity to submit this proposal. If any additional information is needed, please contact us at your convenience. Technical matters should be directed to Dr. Ford at 404/84-5255. Contractual matters should be directed to the undersigned at 404/894-4817.

We look forward to hearing from you soon.

Sincerely,

R. Dennis Palmer

for Jerry Goldbaugh
Contracting Officer

JG/sdm

Addressee: Six (6) copies

CONTINUATION PROPOSAL SUBMITTED TO THE DEPARTMENT OF ENERGY

(DIVISION OF HIGH ENERGY PHYSICS)

by the

Georgia Institute of Technology

Atlanta, Georgia 30332

for

DISSIPATIVE EFFECTS IN THE BEAM-BEAM INTERACTION OF

INTERSECTING STORAGE RINGS

PROPOSED DURATION: Twelve Months

AMOUNT REQUESTED: $ 87,300

REQUESTED STARTING DATE: 1 December 1986

PREVIOUS AWARD: DE-AS05-81ER40003, A007

PRINCIPAL INVESTIGATOR:

Joseph Ford
Regents' Professor
School of Physics
(404) 894-5255

BUSINESS CONTACT:

Jerry Goldbaugh
Contracting Officer
(404) 894-4817

THIS PROPOSAL MAY BE SUBJECTED TO EXTERNAL REVIEW

DISSIPATIVE EFFECTS IN THE BEAM-BEAM INTERACTION OF INTERSECTING STORAGE RINGS

ABSTRACT OF PROPOSED RESEARCH

This proposal seeks continuing support for an on-going research investigation of long-term stability in intersecting, counter-rotating beams of protons and antiprotons confined within high-energy storage rings. Although the dissipative effect of synchrotron radiation in these hadron colliders is anticipated to be a relevant feature affecting beam lifetime, very little is known regarding stability in such many-dimensional, weakly dissipative systems. The work proposed here will analyze the affect of weak dissipation on dynamical instabilities induced by the interaction of synchro-betatron resonances. The object of the research is to obtain conditions for global beam stability over long-time scales as a function of various machine parameters.

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I. INTRODUCTION

This proposal seeks continuing support (previous award: DE-AS05-81ER40003, A007) for an ongoing investigation into the problem of stability for intersecting, counter-rotating beams of protons and antiprotons in storage rings. This challenging problem is currently the subject of intensive research not only because of the difficulty in achieving anticipated design performance but also because of the difficulty of meeting the ever growing need for larger colliding beam facilities.

It is now recognized that vital information about machine performance (luminosity and lifetime as functions of machine parameters, for example) may be obtained by developing models for beam dynamics which can be treated both analytically and numerically. Indeed, this approach can be quite successful provided one permits a delicate interplay between analytical and numerical techniques to aid the solution process. Because truly realistic models are, as a rule, too complicated to be useful for the development of global analytical theories, many of the dynamical processes exhibited by these global models have been extensively studied in isolation using simplified models. For these latter models, the analytical and numerical techniques of modern nonlinear dynamics have proven quite useful for the development of specific theories. However as mentioned, the global simulation of the most general possible particle motion in colliding beam machines is still beyond the scope of modern computers (among other things, the computational times required are much too long), but computers can nonetheless be used to verify significant analytical predictions made by any model and to collate the results of various "local" theories. Indeed, it is precisely this synthesis of analytical and numerical modeling which we shall use to achieve the goals of the work proposed here.

In order to provide the reader with background knowledge for this proposal, we now summarize relevant fundamentals of beam dynamics in storage rings. A more exhaustive introduction to the subject can be found in Refs. [1-4].

II. BACKGROUND

The virtue of counter-rotating beams in a storage ring is that they provide a large center-of-mass energy for the production of desired elementary particle events. Ideally, one would like to create large currents in each beam and maintain them for extended periods of time, thereby maximizing the number of desirable events. This task, however, has proven to be a formidable one. Luminosity and beam lifetime often fall distressingly below their anticipated values due to an unacceptable increase in cross-sectional area of the beams.

From the dynamical viewpoint, these unwelcome effects arise from an increase in the amplitude of transverse oscillations-- the so-called betatron oscillations-- which beam particles execute perpendicular to their ideal circular paths. These oscillations, which are stable when just a single beam is present, can become unstable for counter-rotating beams because the electromagnetic part of the beam-beam interaction causes beam particles to experience a weak, transverse, impulsive "kick" as the spatially bunched beam segments pass through each other. The ultimate goal here is to predict the cumulative effect on beam cross-section of approximately 10^{11} such electromagnetic "kicks;" here the cumulative effect will, of course, depend both on system parameters and on amplitude of betatron oscillations.

In proton-antiproton colliders, the proton beam current is usually considerably larger than that of the antiproton beam because protons are easily obtained in the laboratory while antiprotons are not. Thus, in designing a mathematical model to describe beam motion, one usually neglects the influence of the antiproton ("weak") beam on the proton ("strong") beam and assumes that the latter maintains in time a constant charge distribution. These commonly used assumptions are called the "weak-strong approximation." Using this approximation, one may straightforwardly compute the amplitude of betatron oscillations for the weak beam particles.

"Weak-strong" models for the radial and vertical betatron oscillations describe two coupled, periodically "kicked" oscillators which are nonlinear because the beam-beam force itself is nonlinear. Additional nonlinearities must also be included in the model if, for example, one wishes to incorporate effects due to nonlinear elements in the ring. Because the frequencies of these nonlinear oscillators depend on amplitude, the interaction of the oscillators can become resonant at certain amplitude values, permitting even a very weak interaction to yield a quite large effect. In consequence, these nonlinear resonances have been extensively discussed in the literature, for they are the common source of many distinct mechanisms for beam instability.

It must be noted here that, when many nonlinear resonances act simultaneously, orbital motion can become highly irregular and unpredictably chaotic; specifically the motion can become diffusive. On the other hand, if the perturbation (tune shift) is small, the effect of these multiple resonances is restricted to well-defined domains in phase space--the so-called "stochastic layers" [5]. Size and location of stochastic layers can be controlled by adjusting machine parameters. Indeed, as long as only betatron oscillations in one dimension are considered, global stability criteria valid for all time can, in principle, be formulated. In particular, one can identify stable regimes by determining the parameters ranges for which the largest stochastic layers are well separated from each other in the region of phase space occupied by the beam.

When both radial and vertical betatron motions are taken into account, the problem of long-term beam stability takes on a much greater sophistication. One now has to deal with more complicated resonant structures deriving from the presence of "coupling resonances" and from the related appearance of "weak instabilities," which latter are exponentially slow processes peculiar to systems whose phase space dimensions (including time) exceed four [5,6]. The relevance of these incredibly slow processes to beam stability derives from the truly "astronomical" time scales involved in typical beam-beam experiments where beam particles complete more revolutions about the accelerator ring than the earth has completed about the sun through all time!

Adding to the complexity of the problem, the longitudinal synchrotron oscillations can couple to the betatron oscillations. This coupling can result in the modulation of certain parameters of the beam-beam force and consequently can cause a splitting of each isolated beam-beam resonance into a multiplet of closely spaced synchro-betatron resonances [7]. This configuration of resonances has long been known to have a devastating effect on antiproton beam lifetime, even for very small tune shifts. Indeed, the strong interaction between synchro-betatron resonances causes the appearance of broad domains (modulational layers) in phase space where betatron amplitudes grow through diffusion. The associated weak instability (modulational diffusion [6,8]) is widely regarded as potentially the most dangerous weak instability in hadron colliders. Here, synchrotron oscillations are not usually taken into account explicitly since their effect on the betatron oscillations can be quite accurately simulated through the introduction of suitable parametric modulation.

Finally, the dissipative effect of synchrotron radiation is routinely included in models of electron-positron machines; whereas these effects are systematically neglected in hadron colliders for which conservative, Hamiltonian models have been uniformly employed. However, the radiation emitted by proton beams has actually been detected and measured [9]. Moreover, recent technological advances have achieved an exponential increase in the available center-of-mass energy. Thus, it is quite clear that accurate models for hadron machines must now include weak dissipative effects. In addition, even for small radiation damping, the analysis of these models must include not only the equilibrium configuration of the beam (as in the case of electron-positron colliders) but also temporal phenomena such as chaotic transients or resonance streaming [2]. Having stated these facts, it must now be admitted that the effect of a small dissipation on weak instabilities is currently terra incognita.

III. PROGRESS REPORT ON PREVIOUS AWARD: DE-AS05-81ER40003,A007

A. PUBLICATIONS

Our research has led to the development of new methods for the study of orbits for chaotic dynamical systems having both computational and theoretical interest.

1. I. C. Percival and F. Vivaldi, "Arithmetical Properties of Strongly Chaotic Motions," Physica D (1986), accepted for publication.

2. I. C. Percival and F. Vivaldi, "A Linear Code for the Sawtooth and Cat Maps," Physica D (1986), accepted for publication.

3. G. Mantica and F. Vivaldi, "Beam Stability in a Model of a Storage Ring with Almost Degenerate Betatron Oscillations," J. Nuclear Phys., to be submitted.

4. G. Casati, I. Guarneri, and G. Mantica, "Random Matrices as Models for the Statistics of Quantum Mechanics," Physica D, accepted for publication.

5. J. Ford, "Chaos, Solving the Unsolvable, Predicting the Unpredictable!" in Chaotic Dynamics And Fractals, Edited by M. F. Barnsley and S. G. Demko (Academic Press, New York, 1986).

6. J. Ford, "What Is Chaos, That We Should Be Mindful of It?" in The New Physics, Edited by S. Capelin (Cambridge University Press, Cambridge, 1987).

7. J. Ford, "Quantum Chaos, Is There Any?" in Directions In Chaos, Edited by Hao Bai-Lin (World Scientific Publishing Company, Singapore, 1987)

In Publication 1 above, a new method has been devised for classifying periodic orbits of Hamiltonian systems in strongly chaotic regimes. This method, which exploits certain number-theoretic properties of orbits, allows one to find orbits of any prescribed period and permits one to determine the corresponding initial conditions without explicit computation of the orbits themselves. This approach is particularly suited for numerical computations since it is based on algorithms involving integer arithmetic only, thereby ensuring precision and speed of computation.

In Publication 2, methods of symbolic dynamics are applied to the problem of computing chaotic orbits for a class of nonlinear mappings. Orbits are represented as strings of symbols which are determined via sequences of finite-accuracy measurement on the system. The exact location of orbits in phase space is then reçonstructed by a suitable manipulation of these symbols. Symbolic representation of orbits is found to constitute a much more efficient means of computing chaotic orbits than the conventional procedure of iterating maps explicitly.

Publication 3 considers a two-dimensional Hamiltonian model of the beam-beam interaction for proton-antiproton colliders with bi-Gaussian charge distribution in the strong beam. For special values of certain parameters (equal tunes and cylindrically symmetric charge distribution), an integral of the motion is known to exist which permits reduction to a one degree of freedom system. In Publication 3, a broader range of parameter values surrounding the above "degenerate" set is investigated; here reduction to one degree of freedom is no longer possible. We investigate both analytically and numerically the influence of the broken integral of the motion on medium and long-term stability for particles in the weak beam. We detect the presence of weak instabilities and compute the associated diffusion coefficient. Our results predict strong sensitivity of the antiproton lifetime on tune in the proximity of the main coupling resonance.

Publication 4 examines the problem of decay in correlation functions for fully chaotic dynamical systems. The approach here is through the Wigner Unitary Ensemble of Hermitian matrices, where in addition to each Hermitian matrix H itself, we also consider the associated unitary time evolution operator U = exp(iHt). We verify the occurrence, both analytically and numerically, of a strong decay in autocorrelation function at least up to a critical time related to the rank of the matrix ensemble. Asymptotic formulae are constructed which reveal that, by letting the dimension of the space become infinite, this decay of correlations continues for arbitrarily long times and occurs in the dynamics governed by almost all Hamiltonians in the ensemble.

Publications 5, 6, and 7 review the definition, the meaning, and the significance of chaos for both classical and quantum dynamics. Resolution of the centuries old paradox regarding the co-existence of determinism and randomness (chaos) in dynamics then leads to the conclusion that, contrary to popular opinion, classical dynamics is, in general, fully random whereas quantum mechanics is only partially random. In consequence, the study of chaos appears to be leading to a major revolution which will eventually affect all sciences at every level. But of greater interest here, Publications 5, 6, and 7 are relevant to this proposal because they indicate that chaos-- the ultimate source of the weak instabilities, for example-- is not best described in terms of orbits, as is the current practice, but rather in terms of judiciously chosen probability distribution functions. If such a distribution function approach can indeed be developed, it will likely be much simpler than the present orbital description.

B. SOFTWARE DEVELOPMENTS.

We have devoted much time and effort to the development of efficient numerical tools for the analysis of beam-beam systems.

Various specific codes have been developed as detailed below.

1. Determination Of The Resonant Structure:

Resonant domains are computed up to any given order (using Fourier analysis) and then plotted in both tune and amplitude spaces. The corresponding resonance amplitudes and libration direction are also computed and displayed, using resonant perturbation methods. This analysis provides transparent graphical information about the geometry of the phase space.

2. Determination Of Synchro-Betatron Sideband Overlap:

Sideband resonances are determined for any given resonances as well as the corresponding critical parameters for both sidebands overlap and trapping regime. The size of modulational layers is computed along with the corresponding quasilinear diffusion coefficient.

3. Determination Of Diffusion Coefficients:

Data obtained from particle-tracking are processed and the local coefficient of diffusion in amplitude (or tune) space is computed. A procedure is incorporated to suppress numerical noise, increasing the efficiency of the computation.

IV. PROPOSED RESEARCH

The goal of the research proposed here is to obtain a better understanding of the dynamics of antiprotons beams in the weak-strong regime. This research will develop in two stages:

1. We shall study the global effect of synchro-betatron sideband overlap on antiproton lifetime using the computational tools described in Sec. III.B.2 above. Here, we shall first explore numerically the dependence of the diffusion coefficient inside modulational layers on betatron tunes, tune shifts, and synchrotron frequency. Parameter ranges of practical interest (such as those of the SPS) will be chosen. These computations will be carried through for those amplitudes which correspond to layers associated with the main system resonances. The results will then be compared with the corresponding "local" prediction of the quasilinear theory. This procedure will be used to determine the parameters upon which the diffusion rate depends most sensitively. A global picture of the diffusion rate plotted in amplitude and tune spaces will then be constructed by numerically collating the above "local" results. This procedure will allow us to circumvent the usual difficulties involved in long (and expensive) direct simulations of particle motion. By calculations end, we will be able to predict the most stable regimes for these dynamical systems.

2. We shall analyse the consequences of including weak synchrotron radiation in the calculations just described in the preceding paragraph; specifically a small but physically meaningful amount of dissipation and noise will be added to the dynamics. The

phenomenon of chaotic transient behavior will be studied numerically; on the other hand, resonance streaming can and will be investigated using a combination of analytical and numerical techniques. We also intend to study the influence of noise-induced diffusion relative to dynamical diffusion; here, particular emphasis will be placed on modulational diffusion.

V. REFERENCES

[1] A. A. Kolomensky and A. N. Lebedev, in Theory Of Cyclic Accelerators, (John Wiley and Sons, New York, 1966).

[2] J. L. Tennyson, "The Dynamics of the Beam-Beam Interaction," in Physics Of High Energy Particle Accelerators, A.I.P. Conf. Proc. No. 87 (A.I.P., New York, 1982).

[3] M. V. Berry, in Topics In Nonlinear Dynamics, A.I.P. Conf. Proc. No. 46 (A.I.P., New York, 1978).

[4] See, for example, Physics Of High Energy Particle Accelerators, A.I.P. Conf. Proc. No. 87, Editors R. A. Carrigan, F. R. Hudson, and M. Month (A.I.P., New York, 1982).

[5] B. V. Chirikov, Physics Report 52, 263 (1979).

[6] F. Vivaldi, Rev. Mod. Phys. 56, 737 (1984).

[7] J. L. Tennyson, "The Instability Threshold for Bunched Beams in Isabelle," in Nonlinear Dynamics And The Beam-Beam Interaction, A.I.P. Conf. Proc. No. 57 (A.I.P., New York, 1979).

[8] B. V. Chirikov, M. A. Lieberman, D. L. Shepelyansky, and F. Vivaldi, Physica 14D, 289 (1985).

[9] A. Kofman, "Electron and Proton Beam Diagnostics with Synchrotron Radiation," I.E.E.E. Trans. Nucl. Sci. NS28, 2132 (1981).

VI. COMPUTING FACILITIES

The Rich Electronic Computer Center of the Georgia Institute of Technology provides an excellent environment for performing computations in connection with the proposed research. Its facilities include a CDC 7600 and a CYBER 990, among others. In addition, off-campus vector computers, including a CDC CYBER 205 and a CRAY X-MP are readily available to us via remote communication.

VII. PERSONNEL

A. Professor Joseph Ford (SSN: 267-26-6817) will direct and participate in this research. He will spend full time on teaching and research. He usually teaches one physics course per quarter and directs from one to three graduate students. He received his undergraduate degree from the Georgia Institute of Technology in 1952 and his Ph. D. from the Johns Hopkins University in 1956. Dr. Ford has conducted research under NSF grants G-8799, G-22477, GP-23289, DMR 76-11966, DMR 78-27584, DMR 80-08496, INT 76-21526A01, US-Italy P. 27, Air Force Grant 73-2453, and DOE Grant DE-AS05-81ER40003. He held a NATO Senior Fellowship in Science for three months during the fall of 1973 as a visitor to the University of Milano and Euratom (Ispra). He was a guest of the Soviet Academy of Sciences during the springs 1974, 1976, and 1979, visiting Moscow, Leningrad, and Novosibirsk. He is currently actively collaborating with scientists in Japan, Italy, England,

and the Soviet Union under various international programs. He has been an invited speaker, participant, and/or organizer of numerous international conferences. He has served on the editorial board of the Journal of Mathematical Physics and is a founding Editor of Physica D.

EMPLOYMENT HISTORY

Research Physicist

Location:	Union Carbide Corporation Niagara Falls, New York
Period:	1956 - 1958

Assistant Professor

Location:	University of Miami Coral Gables, Florida
Period:	1958 - 1960

Visiting Professor

Location:	Johns Hopkins University Baltimore, Maryland
Period:	1960 - 1961

Associate Professor

Location:	Georgia Institute of Technology Atlanta, Georgia
Period:	1961 - 1966

Research Participant and Consultant

Location:	Oak Ridge National Laboratory Oak Ridge, Tennessee
Period:	June 1964 - Sept. 1964

Professor

Location:	Georgia Institute of Technology Atlanta, Georgia
Period:	1966 - 1978

Regents' Professor

Location: Georgia Institute of Technology
Atlanta, Georgia
Period: 1978 - present

SELECTED RECENT PUBLICATIONS

"Some Numerical Studies of Arnold Diffusion in a Simple Model," in Nonlinear Dynamics And The Beam-Beam Interaction, A.I.P. Conf. Proc. No. 57 (A.I.P., New York, 1980).

"Modulational Diffusion in Nonlinear Oscillator Systems," in Proc. IX Intl. Conf. On Nonlinear Oscillations, Vol. II, Kiev Naukova Dumka, Kiev (1984), p. 80.

"Analytically Solvable Dynamical Systems Which Are Not Integrable," Physica 13D, 339 (1984).

"One-Dimensional Classical Many-Body System Having a Normal Thermal Conductivity," Phys. Rev. Lett. 52, 1861 (1984).

"Chaos, Solving The Unsolvable, Predicting The Unpredictable!" in Chaotic Dynamics And Fractals, Edited by M. F. Barnsley and S. G. Demko (Academic Press, New York, 1986).

"What Is Chaos, That We Should Be Mindful Of It?" in The New Physics, Edited by S. Capelin (Cambridge University Press, Cambridge, 1987). 1987).

"Quantum Chaos, Is There Any?" in Directions In Chaos, Edited by Hao Bai-Lin (World Scientific Publishing Company, Singapore, 1987).

B. Dr. Giorgio Mantica (SSN: 258-49-5514) will devote himself to this research full time. Funds to cover his salary are requested in the proposed budget. He received his Doctorate degree from the Dipartimento di Fisica, Universitá di Pavia, Italy, in 1982. He became a student of the beam-beam problem while serving as a Postdoctoral Fellow in the Dipartimento di Fisica, Universitá di Milano, Italy. Dr. Mantica has a solid working knowledge of analytical and numerical methods of nonlinear dynamics, both classical and quantal. In recent years, he has accumulated considerable specific experience in computing with vector machines which will be especially valuable for performing the work proposed here.

EMPLOYMENT HISTORY

Postdoctoral Fellow

Location:	Universitá di Milano Milano, ITALY.
Period:	Nov. 1983 - Nov. 1984

Postdoctoral Fellow

Location:	Georgia Institute of Technology Atlanta, Georgia
Period:	Nov. 1984 - present

SELECTED RECENT PUBLICATIONS

"Spectral Fluctuations and Chaos in Quantum Systems," in Chaotic Behavior In Quantum Systems, Edited by Giulio Casati (Plenum Press, New York, 1985).

"Random Matrices as Models for the Statistics of Quantum Mechanics," Physica D, accepted for publication.

"Beam Stability in a Model of a Storage Ring with Almost Degenerate Betatron Oscillations," J. Nuclear Phys., to be submitted.

C. Dr. Franco Vivaldi (SSN: 255-06-5968) will devote one-third of his time to this research and will be paid as a consultant. He received his Doctorate degree from the Universitá di Milano, Italy in April 1977. He has been involved in several international research efforts related to the beam-beam problem. More specifically, he has a broad knowledge of nonlinear dynamics as is demonstrated by the excellent papers produced during his extensive collaborations with Professors Joseph Ford, Giulio Casati, Boris Chirikov, John Greene, Mitchell Feigenbaum, and Ian Percival.

EMPLOYMENT HISTORY

Postdoctoral Fellow

Location:	Georgia Institute of Technology Atlanta, Georgia
Period:	June 1977 - June 1983

Research Scientist

Location:	Georgia Institute of Technology Atlanta, Georgia
Period:	June 1983 - September 1984

Lecturer

Location:	Queen Mary College, University of London Mile End Road, London E1 4NS, ENGLAND.
Period:	October 1984 - Present

Visiting Scientist

Location:	Institute of Nuclear Physics, 630090 Novosibirsk, U.S.S.R.
Period:	October - November 1980 September - October 1981 June 1983 and August 1984

SELECTED RECENT PUBLICATIONS

"Some Numerical Studies of Arnold Diffusion in a Simple Model," in Nonlinear Dynamics And The Beam-Beam Interaction, A.I.P. Conf. Proc. No. 57 (A.I.P., New York, 1980).

"Universal Behavior in Families of Area-Preserving Maps," Physica 3D, 468 (1981).

"The Origin of Long-Time Tails in Strongly Chaotic Systems," Phys. Rev. Lett. 51, 727 (1983).

"The Modulational Diffusion in Nonlinear Oscillator Systems," in Proc. IX Intl. Conf. On Nonlinear Oscillations Vol. II, Kiev Naukova Dumka, Kiev (1984), p. 80.

"Weak Instabilities in Many-Dimensional Hamiltonian Systems," Rev. Mod. Phys. 56, 737 (1984).

"Analytically Solvable Dynamical Systems Which Are Not Integrable," Physica 13D, 339 (1984).

"One-Dimensional Classical Many-Body System Having a Normal Thermal Conductivity," Phys. Rev. Lett. 52, 1861 (1984).

"A Theory of Modulational Diffusion," Physica 14D, 289 (1985).

"Global Stability of a Class of Discontinuous Dual Billiards," Comm. Math. Phys. (1986), to appear.

"Arithmetical Properties of Strongly Chaotic Motions," Physica D (1986), to appear.

VIII. CURRENT SUPPORT AND PENDING APPLICATIONS

The current DOE Contract DE-AS05-81ER40003,A007 constitutes the only off-campus financial support of Professor Ford's research. Similarly, the research of Drs. Mantica and Vivaldi is being supported only by the above DOE Contract. Continuing support from DOE is being sought by the present proposal, and it is being submitted to no other agency.

IX. DESIRED STARTING DATE AND DURATION

The desired staring date is 1 December 1986 and support is requested for twelve months.

X. COMPLIANCE WITH GRAMM-RUDMAN-HOLLINGS

In compliance with the 28 May 1986 letter from Dr. Wallenmeyer, funds in the amount of (4.263%) x ($80,000) = $3,410.40 will remain unexpended at the end of the current contract year, 30 November 1986.

PROPOSED BUDGET

YEAR BEGINNING 1 DECEMBER 1986

A. SALARIES AND WAGES	
1. Senior Personnel	
a. Principal Investigator	
Dr. Joseph Ford	
Full time 2 summer months	$ 13,778
b. Postdoctoral Fellow	
Dr. Giorgio Mantica	
Full time 12 months	$ 18,000
TOTAL SALARIES AND WAGES	$ 31,778
B. STAFF BENEFITS	
(23.6% OF S AND W IN ITEM A.1 a. AND b.)	$ 7,500
C. TOTAL SALARIES, WAGES, AND STAFF BENEFITS (A+B)	$ 39,278
D. PERMANENT EQUIPMENT - none	
E. EXPENDABLE SUPPLIES AND EQUIPMENT	$ 1,000
F. TRAVEL	
1. Domestic - Collaborative research visits to and from Atlanta	$ 2,000
G. PUBLICATION COST - none	
H. COMPUTER COST - none	

I. OTHER COSTS	
1. Subcontract Dr. Franco Vivaldi 1/3 time 12 months plus one London-Atlanta round trip	$ 15,000
J. TOTAL DIRECT COST (C THROUGH I)	$ 57,278
K. INDIRECT COST	
1. (63.5% of Total Direct cost, Item J, Excluding $ 10,000 of item I)	$ 30,022
L. TOTAL COST (J+K)	$ 87,300
M. TOTAL CONTRIBUTION FROM OTHER SOURCES - none	
N. TOTAL ESTIMATED PROJECT COST FOR YEAR (ROUNDED)	$ 87,300

FINAL PROGRESS REPORT ON DOE CONTRACT DE-AS05-81ER40003

PRINCIPAL INVESTIGATOR: JOSEPH FORD

I. INTRODUCTION

This contract has supported more than six years of research into applications of the theories and techniques of nonlinear dynamics to the problem of long-time stability of charged particles in storage rings. Support was initiated on 1 November 1980 and terminated on 31 March 1987. The research was conducted by Professor Joseph Ford, Principal Investigator, in collaboration with Postdoctoral students Dr. Franco Vivaldi and Dr. Giorgio Mantica. This research has also involved domestic and international collaboration with various institutions in the United States, Italy, England, and the Soviet Union. During the last two years of the contract, Dr. Vivaldi served as consultant while a member of the School of Mathematical Sciences, Queen Mary College, University of London.

II. SUMMARY OF RESEARCH

Four main themes of research were developed:

1) LONG-TIME INSTABILITIES INDUCED BY SYNCHROTRON MOTIONS--(MODULATIONAL DIFFUSION)

In order to achieve generality, this phenomenon was studied locally, i. e. near a resonance. We derived an analytic, closed form expression for the local coefficient of modulational diffusion as a function of the synchrotron frequency, perturbation parameter (beam current), and order of the resonance considered. A review of this work can be found in [1], with more technical details being supplied in [2] and [3].

2) DEVELOPMENT OF NEW TECHNIQUES FOR COMPUTING UNSTABLE ORBITS

The problem of developing algorithms for computing chaotic orbits of canonical maps was investigated. Our strategy was to regard strongly chaotic motions as some perturbation of Anosov-type motions, since for the latter, we have developed an arithmetic theory [4]. Methods of symbolic dynamics were then used to construct explicitly orbits for a class of perturbed Anosov systems [5].

3) INTEGRABILITY AND ALGORITHMIC COMPLEXITY

The notion of integrability in Hamiltonian systems was examined critically. The concept of algorithmic integrability was introduced and its relationship to algorithmic complexity theory was clarified [6]. Specific examples of Hamiltonian systems which are algorithmically integrable but not integrable in the usual sense were then introduced and studied [7, 8]. A practical test was devised for identifying the usual integrable systems by examining the structure of singularities in their solutions in the complex time domain [9]. A Hamiltonian system in which integrability and nonintegrability coexist was studied in [10].

4) FOUNDATIONS OF STATISTICAL MECHANICS

We explained the appearance of algebraic rather than exponential decay of autocorrelation functions in strongly chaotic systems [11] and, at the other extreme, we produced the first example of a one-dimensional, many-body system obeying the Fourier law of heat conduction [12].

III. PUBLICATIONS

[1] "Weak Instabilities in Many-Dimensional Hamiltonian Systems," F. Vivaldi, Rev. Mod. Phys. **56**, 734 (1984).

[2] "The Modulational Diffusion in Nonlinear Oscillator Systems," B. V. Chirikov, J. Ford, F. M. Izrailev, D. L. Shepelyansky, and F. Vivaldi, *Proc. IX Intl. Conf. on Nonlinear Oscillations, Vol. II*, Kiev Naukova Dumka, Kiev, 1984 (In Russian) English translation: Preprint 81-70, Institute of Nuclear Physics, Novosibirsk.

[3] "A Theory of Modulational Diffusion," B. V. Chirikov, M. A. Liberman, D. L. Shepelyansky, and F. Vivaldi, Physica **14D**, 289 (1985).

[4] "Arithmetical Properties of Strongly Chaotic Motions," I. C. Percival and F. Vivaldi, Physica **25D**, 105 (1987).

[5] "A Linear Code for the Sawtooth and Cat Maps," I. C. Percival

and F. Vivaldi, Preprint (1986).

[6] "How Random is a Coin Toss?" J. Ford, Phys. Today **36**, 40 (1983).

[7] "Analytically Solvable Dynamical Systems Which Are Not Integrable," B. Eckhardt, J. Ford, and F. Vivaldi, Physica **13D**, 339, (1984).

[8] "Global Stability Of A Class of Discontinuous Dual Billiards," F. Vivaldi and A. V. Shaidenko, Accepted by Comm. Math Phys. (1986).

[9] "Integrable Hamiltonian Systems and the Painleve Property," T. Bountis, H. Segur, and F. Vivaldi, Phys. Rev. **A25**, 1257 (1982).

[10] "Numerical Studies Of Billiard Motions In An Annulus Bounded By Non-Concentric Circles," N. Saito, H. Hirooka, J. Ford, F. Vivaldi, and G. H. Walker, Physica **5D**, 273 (1982).

[11] "The Origin Of Long-Time Tails In Strongly Chaotic Systems," F. Vivaldi, G. Casati, and I. Guarneri, Phys. Rev. Lett. **51**, 727 (1983).

[12] "One-Dimensional Classical Many-Body System Having A Normal Thermal Conductivity," G. Casati, J. Ford, F. Vivaldi, and W. M. Visscher, Phys. Rev. Lett. **52**, 1861 (1984).

[13] "On The Search For Randomness In The Kicked Quantum Rotator," G. Casati, J. Ford, I Guarneri, and F. Vivaldi, Phys. Rev. **A34**, 1413 (1986).

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U.S. DEPARTMENT OF ENERGY

UNIVERSITY-TYPE CONTRACTOR AND GRANTEE RECOMMENDATIONS FOR DISPOSITION OF SCIENTIFIC AND TECHNICAL DOCUMENT

See Instructions on Reverse Side

DOE Report No. DOE/ER/40003-7

Contract No. DE-AS05-81ER40003, A007

3. Title. Dissipative Effects in the Beam-Beam Interaction of Intersecting Storage Rings.

Type of Document ("X" one)

☐ a. Scientific and technical report

☐ b. Conference paper:

Title of conference ______

Date of conference ______

Exact location of conference ______

Sponsoring organization ______

☒ c. Other (Specify Thesis Translations, etc.) Contract Renewal Proposal

Recommended Announcement and Distribution ("X" one)

☒ a. DOE's normal announcement and distribution procedures may be followed.

☐ b. Make available only within DOE and to DOE contractors and other U.S. Government agencies and their contractors.

Reason for Recommended Restrictions

Patent Information

Does this information product disclose any new equipment, process or material? ☐ Yes ☒ No

Has an invention disclosure been submitted to DOE covering any aspect of this information product? If so, identify the DOE (or other) disclosure number and to whom the disclosure was submitted. ☐ Yes ☒ No

Are there any patent related objections to the release of this information product? If so, state these objections.

Submitted by — Name and Position (Please print or type)

Dr. Joseph Ford, Regents' Professor

Organization

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332

Signature Joseph Ford — Date 7/22/86

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Patent Clearance ("x" one)

☐ a. DOE patent clearance has been granted by responsible DOE patent group.

☐ b. Report has been sent to responsible DOE patent group for clearance.

☐ c. Patent clearance not required.